Net Land Gain or Loss for Two Mississippi River Diversions: Caernarvon and Davis Pond

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Running head: validating river diversion gains and losses

Abstract

Coastal wetland restoration can be complex and expensive, and so knowing long-term consequences makes it important to inform decisions about if, when, and where to conduct restoration. We determined temporal changes in land gain and loss in receiving basins and adjacent reference areas for two diversions of the Mississippi River in south Louisiana (Davis Pond and Caernarvon initiated in 1991 and 2002, respectively). Water from both diversions went

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into receiving basin with vegetated areas as did the adjoining reference areas. The results from two different types of satellite imagery analyses demonstrate a net land loss after diversions began. The results were confirmed for the Caernarvon diversion using a before-after/control-impact analysis of independently collected data over a larger area of the estuary. These results are consistent with an analysis of land gain and loss after a natural levee break on the Mississippi River in 1973. The positive influence of adding new sediments were apparently counter-balanced by other factors, and consistent with the conclusion from other studies indicating that increased nutrient supply and flooding are, by themselves, negative influences on marsh health. Modeling the ecosystem effects of diversions can be calibrated and tested using landscape-scale analyses like this to understand the chronic and delayed effects, including the unintended consequences. Basing the legitimacy of river diversion on ecosystem modeling will be premature without successfully reproducing empirical results like these in ecosystem models.

Keywords: wetlands, river diversions, restoration, land loss and gain

Implications for practice:

• The net land loss after the Mississippi River was diverted through three diversions suggests that the rationale to build them was inadequate;

• Ecosystem models should reproduce landscape changes at these diversion locations before building new diversions, in order to train new models and reduce predictive errors.

• The inclusion and evaluation of meaningful monitoring at a landscape scale, not just small-scale experimentation, should be included in an adaptive management scheme to fully assess future restoration conditions.

• Both flooding and increased nutrient availability are threats to coastal marsh survival on coastal plains

Introduction

The availability of dredges, pumps, conveyance pipes and channels, etc., make it possible to move large amounts of sediments and water over great distances or to restrict water movements with an extensive system of levees. Conspicuous large coastal projects include the levee construction and hydraulic management of Roman land reclamations (Ribbon 2000) and Dutch polders (Danner et al. 2005), and levee de-constructions involved in coastal retreat in England (Boumans & Hazelden 2017). Today's projects are framed in the uncertain world of sea level rise, storms and hydrologic anomalies, and also with the consequences that biological factors - the levees may fail from burrowing animals, soil subsidence lowers marsh elevation, plant communities change, and tidal restrictions and sea level rise have consequences for soil and plants (Silliman et al. 2009; Roman 2017; Turner et al. 2018a). Ecosystem models can be a heuristic device to explore and predict the consequences of these known and unrealized conditions. Model uncertainty is reduced by populating them with field data.

A large and modern restoration project on the Louisiana coast is where about 25% of the 1.95 million ha coastal wetlands existing in the 1930s are now open water (Couvillion et al.

2016). The primary driving force causing land loss over the entire deltaic plain was the dredging of 16,853 km of canals and waterways for oil and gas recovery whose temporal rise and fall across the coast, and spatial distribution within is coincidental with land loss rates (Turner & McClenachan 2018b). Over 200 years, the rise and fall of the size of the wetlands in the subsection of deltaic plain known as the 'birdfoot' delta, located at the terminal end of the Mississippi River, was driven by proportional changes in sediment supply as soils were eroded during colonization and then reduced with soil conservation and sediment trapping behind dams (Meade 2010; Tweel & Turner 2012; Turner 2017). In order to address these landscape changes Louisiana developed a restoration plan called the Louisiana's Comprehensive Master Plan for a Sustainable Coast, (Master Plan; CPRA 2017). The Master Plan includes $5.1 billion (US) for river diversions to move water and sediments from the Mississippi River into adjacent wetlands with the intention of maintaining and expanding them. However, the century-long nutrient enrichment of the diverted water may increase the decomposition rates of the accumulated organics, reduce root strength, and minimize roots and rhizome biomass as the pressure for nutrient foraging is eased (Swarzenski et al. 2008; Kearney et al. 2011; Turner 2011; Deegan et al. 2012; Hollis & Turner 2019). There is also uncertainty about the consequences of wetland freshening (Howes et al. 2010), a declining sediment load of the river (Mize et al. 2015), social costs (Caffry et al. 2014), the physiological consequences of flooding from the diverted water, increased storm frequency, and sea level rise (Hansen et al. 2016; Morris et al. 2016; Turner et al. 2018a).

Two ecosystems models explore the complexity of these interrelated factors whose physical forcings (e.g. salinity, water depth, and sediment deposition) are supported by field measurements made at a landscape scale and in laboratory studies. The Mid-Breton diversion (east bank of the Mississippi River) and Mid-Barataria (west bank of the Mississippi River) diversion are proposed to be built below New Orleans and were modeled by Brown et al. (2018) using a discharge of 141.6 and 1416 m^{-3} s^{-1}, respectively (Table 6.3; Brown et al. 2019). The Brown et al. (2019) and Baustian et al. (2018) models predict net land gain near the diversion outlets as result of sand accumulation, and loss further way as a result of plant inundation and minimal sediment accumulation. Predictive results from the two models diverge when they predict the inundation effects on wetlands (Brown et al. 2019). Wetland vegetative growth is exclusively a function of local water depth in the Brown et al. (2019) model which says that "Significant uncertainty exists with respect to the response of the existing wetland vegetation to diversion-induced inundation." (abstract). The Baustian et al. (2018) model is dependent on an 'expert assessment' for 9 of 14 validations for model components (http://coastal.la.gov/wp-content/uploads/2017/04/Attachment-C3-1_FINAL_02.22.2017.pdf; Table 3), implying that these are partly subjective conclusions that will be less definitive than the equations calculating hydrologic flow and sediment transport. Neither model includes a quantified consideration of the 30% decline in root strength (Hollis & Turner 2019) or soil strength (Turner et al 2011) after small increases in nutrient availability, which Baustian et al. (2018, p. 415) suggest is a concern. The interactive effect of hurricanes and diversions is not included, and land gain or loss in wetland soils beyond the initial outfall area are not used to calibrate either model. The Brown et

al. (2019) model validates the area of delta formation in the outfall area of the Caernarvon diversion, but not in the far-field. The changes in the West Bay diversion (birdfoot delta) that are used to validate their model are for an area that has open water areas overlying mineral soils, and the model uses sediment deposition, not land area as the metric. The far-field inundation of wetlands, therefore, is not significant in the West Bay diversion, unlike for the two proposed diversions located northward and halfway to New Orleans (Brown et al. 2018). These latter two diversions go into shallower water with wetlands.

We agree, therefore, with a recent qualitative assessment of possible ecosystem responses to diversions by Quirk et al. (2019): “Many of these interactions cannot be fully assessed through small-scale experimentation and thus, diversions will also serve as an important model through which to further test hypotheses and inform future management”. Land-water changes occurring from existing man-made river diversions can inform coastal management plans. The quantified results can populate restoration models and be used to develop adaptive management strategies, to exploit more favorable outcomes and to minimize or avoid undesirable outcomes.

Here we measure the relative changes in land gain and loss for two diversions to test the hypothesis that river diversions stimulate land building. A specific objective is to determine the land-building consequences of the two diversions of the Mississippi River that have been operating since 2002 (Davis Pond) and 1992 (Caernarvon). Simply put, did land loss rates increase, stabilize, or decline after diversions become operational? We address this question using: 1) two different remotely sensed imagery analyses (Data 1 and Data 2) of the percent land in the diversion flow path and adjacent reference areas that are specific to each diversion, and, 2)

a BACI (before-after, control-impact) analysis of independently developed data for one diversion. We examine differences in the percent land area before and after the diversion became operational using the average percent land for the intervals, and, the relative slopes of the percent land versus year. The results, regardless of whether there is a land loss or gain, can populate models with on-the-ground data, reduce the uncertainty in model predictions, and be used to inform policy.

Methods

Experimental Design

Two river diversions were examined: Davis Pond and Caernarvon. The Davis Pond diversion is between Baton Rouge and New Orleans (190.5 km above the birdfoot delta), and Caernarvon is 24 km downstream from New Orleans (131 km above the birdfoot delta; Figure 1). We identified pixels as either land or water within files overlaid on all GIS maps. The areas designated as receiving basin had levees on the east and west side sides and open water to the south. Swamp and developed areas were excluded. The definition of what is a receiving basin is partly subjective, in that diversion water flows beyond it and into the entire estuary. In this sense, the entire estuary is the receiving basin. We used the receiving basin defined by the project in State of Louisiana defined restoration boundaries. The receiving basins are separated from the reference area by a natural or constructed levee. The Caernarvon diversion flow path closest to the diversion outfall (location a) continues far beyond the diversion discharge point. The reference areas are therefore, partially isolated from the water flowing through the diversion’s

downstream path, but some water enters into reference areas at the downstream end of the diversion outfall area (Figure 1). A second reference area outside of the hydrologic unit location b) is located to the east that is adjacent to the Caernarvon diversion area and receives some minor amounts of diversion water through an opening in the levee at Regio, LA, on the eastern edge of the estuarine watershed. This area is the same reference area defined by Kearney et al. (2012) in their study of landloss in the area.

The land area for each diversion and reference area is in Table 1, along with the 1st year operating date, design capacity, and anticipated land area to be benefitted as determined before the diversion opened. The Davis Pond and Caernarvon diversions are the largest two sites in terms of discharge capacity and anticipated influence. The oldest diversion is Caernarvon, located on the east side of the descending bank below New Orleans. The maximum flow capacity there is 227 m^{-3} s^{-1}, and it began operations after 1991. Caernarvon was projected to benefit or create 396 km^2 of wetlands by delivering sediments and freshwater (USCOE 2004). The largest diversion is Davis Pond, which began operation in 2002, has a design capacity of 396 m^{-3} $s^{-1}$and was projected to benefit or enhance at least 3,278 km^2 wetlands (USCOE 2004).

Table 1. The diversion starting date (year), maximum flow capacity (m^{-3} s^{-1}), study area size (km^2), and anticipated land gain or preservation in agency documents.

We examined State and Federal records to estimate the average discharge for each diversion. The diversion daily discharge did not usually reach the design capacity. The Caernarvon diversion from January 2000 to August 2018 had an average discharge of 41.8 m^{-3} s^{-}

[1]; the Davis Pond diversion from January 2002 to August 2018 had an average discharge of 46.1 m^{-3} s^{-1}. Graphs of the daily discharge at each are in the supplemental materials (Figure S1).

Satellite imagery

The land loss in each area was determined using two remote sensing imagery analyses that estimated the percent land in multiple years beginning in 1985. The data sets were developed using Landsat satellites equipped with different multispectral sensors. The Landsat 5, equipped with Thematic Mapper, was launched in 1984 and decommissioned in 2011; Landsat 7 was launched in 1999 and equipped with Enhanced Thematic Mapper Plus; Landsat 8 was launched in 2013 and equipped with an Operational Land Imager. These sensors have a spatial resolution of 30 m and a temporal revisit cycle of 16 d. The results from using the two data sets are classified herein as either land or water, but not wetland, because some pixels may be roads or structures, even though overwhelmingly composed of emergent wetland.

The first data set (Data 1) was primarily developed to measure seasonal changes in wetland greenness (revealing phenological changes; Mo et al. 2019). We used ninety-one cloud-free Landsat Climatic Data Records (CDRs) images (mosaics of Scenes of Path 22 Row 40 and Path 22 Row 39) collected from 1985 to 2014 to estimate the wetland area (range 1 to 4 images y^{-1}). The Landsat CDRs were pre-processed using the Landsat Ecosystem Disturbance Adaptive Processing System atmosphere correction tool by Schmidt et al. (2013). Further processing of the data was performed using ENVI 4.8 (ITT Exelis, USA). The wetland area was estimated using the C version of the Function Mask (CFMask) with the Landsat CDRs. The overall accuracy of

the CFMask to estimate the wetland area is 0.89 ± 0.04% (verified with the USGS Digital Orthophoto Quadrangle, DOQs) (Mo et al. 2019).

The second data set (Data 2) is from 1985 to 2015 and is described by Couvillion et al. (2016) and located at: https://www.sciencebase.gov/catalog/item/5a67a8cde4b06e28e9c57150. These authors classified pixels into land and water categories using a modified Normalized Difference Water Index (NDWI) that uses the near-infared wavelengths (1.55 - 1.75 micrometers) to reduce signal noise from land, vegetation, and soil (Xu 2006). A supervised and unsupervised classification was then used to correct for areas incorrectly classified by using only the NDWI. These steps were manually recoded by expert analysis (Couvillion 2017). The resulting data set was further classified to record only the changes occurring between two successive dating intervals in sequence (persistent changes). Data 2 is used by State and Federal programs to monitor land-loss trends for the whole coast and changes within specific restoration project areas (Couvillion 2017).

The two data sets define different kinds of land loss rates. Data 1 is from 1985 to 2014 and Data 2 is from 1985 to 2015. Data 2 includes relatively less floating vegetation classified as land than do land estimates using Data 1 because seasonal and annual changes in floating vegetation within one pixel are not measured as land loss unless they are also observed in the next aerial image. This methodological difference results in a more conservative estimate of the percent land for Data 2 compared to Data 1, and reduces variance from year to year..

The land area in the two diversion areas was converted to the percent of land in 1985 as a common starting point, which was normalized (= 100%). The data were sub-divided into periods

for before and after each of the diversions were first opened. The opening date is shown as a dotted vertical line in figures. The Caernarvon data collected after the diversion was opened was further divided into periods before and after hurricane Katrina passed directly over the reference site.

CRMS data

A third data set measuring land in the Caernarvon diversion area is from the Coastwide Reference Monitoring System (CRMS) administered by the Louisiana's Coastal Protection and Restoration Authority. This data set includes measurements of plant cover in geographically fixed 1 km^2 sites using satellite data (Louisiana Department of Natural Resources Coastal Monitoring Program). There are 14 sites within the Caernarvon flow path and 18 outside of the flow path located to the east, north and west. We compiled the mean ± 1 SEM (standard error of the mean) of the percent plant cover values for the 65 times that measurements were made for each quadrat from 1985 to 2016, and allocated the values for inside and outside of the flow path. The time periods were for: 1) before the diversion was operational in 1991, 2) after operation began, but before Hurricane Katrina, and, 3) after Hurricane Katrina (n = 8, 16, and 11 years, respectively). The data for CRMS stations within the Caernarvon diversion flow path of Breton Sound were also sub-divided into the 7 northern and the 7 southern stations.

Statistical Analysis

Linear regressions of the percent land vs. year, were calculated for each time interval for the two river diversions using a $p < 0.05$ as the threshold to determining significance. We used Prism software to test if there were significant slopes (% y^{-1}) within each interval, and then tested for a difference in slope within each area for before and after the diversion was opened. The comparison calculates a p value derived from an analysis of covariance (two-tailed) testing the null hypothesis that the slopes are identical (i.e., the lines are parallel). The before and after slopes for reference and diversion areas were then compared to each other ($p < 0.05$) to test for differences in slope. The intervals for the 'after' comparison using the Caernarvon data ended when Hurricane Katrina occurred in 2005.

The absolute rates of land loss (% y^{-1}) in reference and diversion areas before the diversion opened could be different from each other for a variety of reasons unrelated to a diversion operating. We used the relative changes in slopes to determine if there were effects after the diversion opening; we asked, therefore, if the changes (before-after) were higher or lower in the diversion flow path than in the reference site.

The land area data for the CRMS station had multiple stations sampled at the same time over many years from both reference and diversion areas. These data were used to perform a Before-After, Control-Impact (BACI) analysis (Underwood 1994) using the General Linear Models (GLM) procedure in SAS/STAT software (Version 9.4 TS level 1M2) of the SAS System for Windows (Copyright © (2002-2012) SAS Institute Inc., Cary, NC, USA). The BACI model was originally formulated to test if an impact occurred, however it is now mainly used to test if a change occurred (Smith 2002). The "Before" and "After "classes are based upon the

timing of the event being studied (diversion or hurricane). The "Control stations" were the CRMS stations outside of the diversion flow path and the "Impact" stations were the CRMS stations within the diversion flow path.

The BACI model looked at the interaction of the "Before-After" and the "Control-Impact" statistical tests. In using the model, the data is divided into "Before" and "After" and "Control" and "Impact" classes. The basic model is:

Response Variable = BA + YEAR(BA) + CI STATION(CI)

+ BA*CI + YEAR*BA*STATION(CI)

where BA denotes Before/After class, YEAR denotes measurement over time, CI denotes Control/Impact class, a ‘*’ denotes an interaction term and parentheses indicate nesting. In the BACI analysis the main effects are not of interest, only the interaction. In order to show an impact, the BA*CI interaction term must be significant (McDonald et al 2000).

It is possible to have a difference between the Control and Impact stations (the CI term in the model would be significant) without an actual impact due to the event if the difference between stations is always present. Similarly, it is possible to have a difference between the Before and After samples (the BA term in the model would be significant) without an actual impact due to the event if all stations had the same response (i.e., all of the stations increased by the same amount after the event). A significant BA*CI term indicates that the Impact stations are responding differently than the Control stations to the event.

The standard BACI model was run under four scenarios:

BA1: Before = Pre-diversion years; After = post diversion years

BA2: Before = Pre-diversion years; After = post diversion, but pre-hurricane years

BA3: Before = Post diversion years, but before the hurricane; After = post hurricane years

BA4: Before = Pre-diversion years; After = post hurricane years

The mean and standard error (μ ± 1 SEM) were computed for each year for all seven southern and all seven northern stations used for the BACI model, and a linear regression equation made of all values for each year.

Results

The range in % land cover (normalized to the 1985 values = 100%) for each of the intervals ranged from 56.3 to 118.0 % y^{-1} for Data 1 and from 54.4 to 100.0 % y^{-1} for Data 2. The slopes (% y^{-1}) ranged from no changes using Data 1 to -1.07 % y^{-1} for Data 2. The results for each study area are discussed below in terms of the relative changes in land loss in the reference area and in the diversion flow paths for before and after the diversion opened.

Davis Pond diversion

The percent land in the reference site at the Davis Pond was equal before and after the diversion opened using Data 1 (mean = 95.9 and 95.4%, respectively) and slightly higher in the diversion site using Data 2 (mean = 99.4 and 98.0%, respectively). The visual appearance of the annual trends demonstrates the higher variability from year to year for Data 1 compared to Data 2 (Figure 2), which is a consequence of how the two data sets were compiled. Data 2 is a more

conservative metric because of the definition of change requires two consecutive interpretations of land conversion to land (or from water to land) for each pixel. There was a significant relationship between year and the percent land for all intervals in the reference and diversion sites using Data 2 ($p<0.01$), but not Data 1 (Figure 2A, B; $p>0.05$; Table S1). The slope of the percent land vs. year for Data 2 was slightly lower in the reference site compared to after the diversion opening (-0.06 and -0.27% y^{-1}, respectively; F = 27.8. $p<0.01$; Table S1), and the slope in the diversion flow path was lower before opening compared to afterwards (-0.36% y^{-1} and -1.07% y^{-1}, respectively; F = 48.7. $p<0.01$; Table S1). The Data 2 slope in the diversion flow path before the opening, however, was lower (difference = -0.36 % y^{-1}; F = 208, $p<0.01$; Table S1) than in the reference site (difference = -0.60 % y^{-1}; F = 162, $p<0.01$; Table S1), so that the relative difference in the reference site compared to the diversion flow path was -0.49 % y^{-1} after the diversion was opened. We conclude that the percent land loss at Davis Pond remained stable at the reference site, but decreased significantly within the diversion flow path after it was opened at an enhanced loss rate of -0.49% y^{-1}.

Caernarvon diversion

The results from the analysis of the Caernarvon diversion area provides a more complex picture for the first few years after the diversion opened (from 1992 to 2005) compared to after Hurricane Katrina (2010). The highest average % land area then was in the reference area for Data 1, location b (110.0 %), and ranged from 98.1 to 99.27 % in the other five areas. There were no significant slopes (% y^{-1}) for any interval using Data 1, or change in them before or after

the diversion opened. The % land in the diversion area using both Data 1 and 2 was slightly higher compared to in the reference area before hurricane Katrina, but was dramatically different afterwards (Figure 2E, F). The % land using Data 1 did not decrease after the diversion opened, but decreased after hurricane Katrina and then recovered (Figure 2C, D). Post-hurricane, however, the % land in the diversion flow path remained above the % land in the reference location a, but fell below the % land in the reference area in reference location b. The analysis of Data 2 revealed no significant difference in the loss rates at the reference or diversion locations a and b *after* the diversion opened but before 2010. There were significant losses in all areas after 2010 (Table S1).

Cumulative changes

A summary of the relative differences between the changing slopes, or not, for Data 2 is in Figure 3 for the three comparisons. The relative differences between land loss rates in reference and diversion areas in Davis Pond (Figure 3A) were increasing before the opening of the diversion; the reference area declined slower compared to the reference site, and so the slope is decreasing. The decline in % land increased even faster than in the reference area after the diversion opened because of the increased land loss in the diversion area. The percent land in the Caernarvon area at the references site compared to in the diversion flow path were not different before or after the diversion opened, but before hurricane Katrina passed over both areas (Figure 3B, C). The % land area in the reference site then was changing at a slower rate than in the flow path and so the slope is positive. After the hurricane, however, the % land in the diversion flow

path dropped relative to in the reference area, particularly for location b. It had not recovered by 2015. The data suggest, therefore, that the Caernarvon diversion had no effect on increasing loss rates in the flow path immediately after the diversion opening; after the hurricane, however, the loss rates increased substantially in the diversion flow path in location b, but and less so in location a.

BACI test

The results from the BACI test for the Caernarvon data (Figure 4; Table S2) demonstrated a significant Control-Impact interaction term for intervals BC1, BC3, and BC4, indicating that there was a different response between the Control and Impact sites. There was no increase in the percent land within the flow path (restoration or rehabilitation) from 2010 through 2016 (Figure 4). The percent land was the same in the 14 reference sites before the diversion opened compared to afterwards (but before the hurricane) (p >0.05), but lower in the flow path after the hurricane (p< 0.001; Figure 4). The interaction term was not significant for interval BC2 indicating that the control and impact sites had the same rate of change. The average percent land in the seven northern and the seven southern CRMS stations changed coincidentally from 1985 to 2016 (Figure S2), and the average percent land for the southern stations was a consistent 70% of that in the northern stations (R^2 = 0.79; Figure S2), which confirms that the watershed is an integrated basin in terms of land losses and gains. These results are consistent with the results from the ANOVA analysis of the aerial imagery for the Caernarvon diversion.

Discussion

Two first-order observations are: 1) there is no evidence of a change in net land gain or conservation within the two sites after the diversion operation began, and 2) there is clear evidence of higher land loss rates within a few years after the Davis Pond diversion opened. The Caernarvon diversion had no appreciable land gain, and perhaps a slight land loss in the first few years after it opened, and then considerable losses after Hurricane Katrina which were about 25% of the larger area (Kearney et al 2011). We measured land loss after Hurricane Katrina that was about one-third of the wetlands in the flow path, which is a comparable loss to when the natural diversion occurred at Fort St. Philip in 1973 (Suir et al. 2014). There the loss was 58% of the surveyed area and has not been restored after 38 years. The Fort St. Philip diversion was about 12 times larger at maximum flood than the potential discharge size at Caernarvon, and one-third larger than the flow capacity of diversions proposed in the Master Plan. The discharge at Fort St. Philip is not monitored on a regular basis, and so further comparisons are not possible with the data presented here.

The result of the Brown et al. (2018) modeling analysis of net land change for several diversions was that “none of the scenarios tested have a net land gain, due to the losses of land incurred from inundation of the vegetation.” (p. 111). They estimated that these inundation effects are an “overwhelming source of uncertainty” in the model results (p. 97), and so we think that model improvements might change outcomes to produce different outcomes, including net gains or losses. That uncertainty might be reduced by incorporating the decades-long land-loss

rates of the diversions studied here. The areas we used as the flow path and reference zones could be enlarged, substituted, or shrunk in order to implement such a model training.

Diverting river water to the adjacent wetlands increases sediment supply, but also affects plant flooding and nutrient availability, but not equally across the landscape. The heavier soil particles (principally sand) introduced with diversions fall out quickly as river currents slow in an open water body, whereas the remaining suspended particles spread out over a larger area and with eventual an capture efficiency on the deltaic plain of roughly 30 – 70% (Blum and Roberts 2009). The water and its nutrients are distributed horizontally and vertically far beyond where the sand particles accumulation.

The diverted water floods the marsh for longer and more frequent intervals, which is a well-recognized plant stress (Mitsch and Gosselink 2007; Keddy 2011). Further, the nutrient concentrations in the modern Mississippi River are much higher than when the organic content of the sediment accumulated centuries ago (Turner et al. 2007; Tweel & Turner 2012). The increased nutrient availability in the receiving basin may cause lower belowground biomass because: 1) the accumulated organic matter may decompose faster; 2) the reduced pressure for plants to forage for nutrients leads to a smaller attached belowground biomass (Darby & Turner 2008; Turner et al. 2018); 3) it results in weakened individual roots as the internal structure of roots adapts to flooding and nutrients (Hollis &Turner 2019), and, 4) perennial plants replace annuals to alter the vertical distribution of roots (Howes et al. 2010). These four factors cause a loss in soil strength (Turner 2011). The sediments then become more susceptible to erosion during high water events or from hurricanes (Kearney et al. 2011; Howes et al. 2010). The

combined stress of inundation and increased nutrient availability is one explanation for why wetlands converted to open water in the Caernarvon diversion flow path after hurricane Katrina and have not re-vegetated (Figs. 4), whereas the reference wetlands are losing land at the same rate as before the diversion opened even though the hurricane passed right over it (Fig. 2F). Other hurricanes, including Hurricane Betsy in 1963, also passed nearby and did not cause this amount of reduction in the percentage of land. From 1956 to 1973, for example, the percent land in the diversion flow path and at the reference sites decreased by 5% (Couvillion 2017), whereas it declined about 20% after Hurricane Katrina.

The two diversions analyzed here are distinctly different from the Atchafalaya Delta located westward in the middle of the coast and sometimes described as a river diversion. The Atchafalaya River carries 30% of the Mississippi River that is sent through a water control structure near St. Francisville, LA to join with the Red River to create the Atchafalaya River. Unlike the Davis Pond and Caernarvon diversions. The Atchafalaya River discharges into the open water that overly mineral soils, and not into the shallow water and organic-rich wetland soils of the Caernarvon and Davis Pond diversions (Turner 2017). The far-field effects of nutrients and inundation on vegetation are immaterial there. Further, the Mississippi River main channel below New Orleans traps almost all of the land-building materials (Allison et al. 2012), which means that an upstream diversion of sediments diminishes land-building or maintenance downstream, leading to a zero-sum land area change for the whole delta (Turner 2017).

This analytical approach provides data to populate models with empirical data collected at a landscape scale; other areas might also be compared and we recommend doing that using the

Data 2, not Data 1, because there is less floating vegetation represented in Data 2. Regardless of the data used, the model results must accurately reflect the empirical results, even if the underlying causes are not understood. The cost, efficacy, and duration of ecological restoration is illuminated, developed and improved by incorporating the empirically-defined field data, especially in a newly developing modeling field like coastal wetland restoration (Zedler 2017). The inclusion and evaluation of meaningful monitoring at a landscape scale should be included in an adaptive management scheme to know if the management action was successful or not (Ralph and Poole 2003; Zedler 2017). Not doing this surely results in a higher scientific uncertainty and reduces public trust. The anticipated benefits of two diversions were not realized which supports a recommendation to 'do no harm'. Implementing the proposed river diversions in the Master Plan appears premature because the modeling is incomplete, and the empirical results from three nearby diversion are not replicated in model outputs.

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References

Allison MA, Demas, CR, Ebersole, BA, Kleiss, BA, Little, CD, Meselhe, EA, Powell, NJ, Pratt, TC, Vosburg, BM (2012) A water and sediment budget for the lower Mississippi-Atchafalaya River in flood years 2008-2010: Implications for sediment discharge to the oceans and coastal restoration in Louisiana. Journal of Hydrology 432:84–97

Baustian, MM, Meselhe E, Jung, H, Sadid, K, Duke-Sylvester, S.M, Visser, J.M, Mead A. Mossa LC, Ramatchandiran, C, van Sebastiaan van Maren, D, Meuken, M, and S. Bargu (2018). Development of an Integrated Biophysical Model to represent morphological and ecological processes in a changing deltaic and coastal ecosystem. Environmental Modelling & Software 109402-419

Blum, MD, HH Roberts (2009). Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nature Geoscience 2(7):488-491

Brown GL, McAlpin JN, Kimberly N, Pevey KC, Luong PV, Price CR, Kleiss, BA (2019) Mississippi River hydrodynamic and delta management study: Delta management modeling: AdH/SEDLIB multi-dimensional model validation and scenario analysis report. U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS, Report ERDC/CHL TR-19-2; http://acwc.sdp.sirsi.net/client/default

Brown GL, McAlpin JN, Kimberly N, Pevey KC, Luong PV, Price CR, Kleiss, BA (2019) Mississippi River hydrodynamic and delta management study: Delta management modeling: AdH/SEDLIB multi-dimensional model validation and scenario analysis report. U.S. Army

Engineer Research and Development Center (ERDC), Vicksburg, MS, Report ERDC/CHL TR-19-2; http://acwc.sdp.sirsi.net/client/default

Caffry RH, Wang H, Petrolia DR (2014) Trajectory economics: Assessing the flow of ecosystem services from coastal restoration. Ecological Economics 100:74–84

Couvillion BR, Beck H, Schoolmaster D, Fischer M (2017) Land area change in coastal Louisiana 1932 to 2016. U.S. Geological Survey Scientific Investigations Map 3381

Couvillion BR, Fisher MR, Beck HJ, Sleavin WJ (2016) Spatial configuration trends in coastal Louisiana from 1985 to 2010. Wetlands 36:347–359

CPRA (Coastal Protection and Restoration Authority) (2017) Louisiana's Comprehensive Master Plan for a Sustainable Coast 2017; Available from: http://coastal.la.gov/our-plan/2017-coastal-master-plan/

Danner HS, Renes Toussaint JB, van de Ven GP, Zeiler FD. [Eds.] (2006) Polder pioneers: The influence of Dutch engineers on water management in Europe, 1600-2000. Nederlandse Geographical Studies 338

Darby FA, Turner RE, (2008) Below- and aboveground biomass of *Spartina alterniflora*: Response to nutrient addition in a Louisiana salt marsh. Estuaries and Coasts 31:326-334

Deegan LA, Johnson DS, Warren RS, Peterson BJ, Fleeger JW, Fagherazzi S,Wollheim WM, 2012. Coastal eutrophication as a driver of salt marsh loss. Nature 490:388–392

Elsey-Quirk T, Graham SA, Mendelssohn IA, Sneden G, Day JW, Twilley RR, Shaffer G, Sharp LA, Pahl J, Lane RR 2019. Mississippi River sediment diversions and coastal wetland

sustainability: Synthesis of responses to freshwater, sediment, and nutrient inputs. Estuarine, Coastal and Shelf Science 221:170-183

Hansen J, Sato M, Hearty P, Ruedy R, Kelley M, Masson-Delmotte V, Russell G, Tselioudis G, Cao J, Rignot E, Velicogna I, Tormey B, Donovan B, Kandiano E, von Schuckmann K, Kharecha P, Legrande AN, Bauer M, Lo K-W (2016) Ice melt, sea level rise and superstorms: Evidence from paleoclimatedata, climate modeling, and modern observations that 2 °C global warming could be dangerous. Atmospheric Chemistry and Physics 16:3761–3812

Hollis LO, Turner RE (2019) The tensile root strength of *Spartina patens*: Response to atrazine exposure and nutrient addition. Wetlands on line. 10.1007/s13157-019-01126-1

Howes NC, FitzGerald DM, Hughes ZJ, Georgiou IY, Kulp MA, Miner MD, Smith JM, Barras JA (2010) Hurricane-induced failure of low salinity wetlands. Proceedings of the National Academics of Sciences (USA) 107:14014–14019

Kearney MS, Riter JCA, Turner RE (2011) Freshwater river diversions for marsh restoration in Louisiana: Twenty-six years of changing vegetative cover and marsh area. Geophysical Research Letters 38: doi: 10.1029/2011GL047847

Keddy PA (2011) Wetland Ecology: principles and conservation 2nd Edition. Cambridge University Press, Cambridge, England

Louisiana Department of Natural Resources Coastal Monitoring Program (http://lacoast.gov/crms2/). Accessed 30 August 2018

Meade, RH, and JA Moody (2010) Causes for the decline of suspended-sediment discharge in the Mississippi River system, 1940–2007. Hydrological Processes 24:35–49

Morris JT, Barber DC, Callaway JC, Chambers R, Hagen SC, Hopkinson CS, Johnson BJ, Megonigal P, Newbauer SC, Toxler T, Wigand C (2016) Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state. Earth's Future 2016; 4, doi:10.1002/2015EF000334

McDonald TL, Erickson WP, McDonald LL (2000) Analysis of count data from before-after control-impact Studies. Journal Agricultural, Biological, Environmental Statistics 5:262-279

Mitsch, WJ, and JG Gosselink (2007) Wetlands, 4th ed. John Wiley & Sons, New York

Mize SV, Murphy JC, Diehl TH, Demcheck DK (2018) Suspended-sediment concentrations and loads in the lower Mississippi and Atchafalaya rivers decreased by half between 1980 and 2015. Journal of Hydrology 564:1–11

Mo Y, Kearney MS, Turner RE (2019) Feedback of coastal marshes to climate change: Long-term phenological shifts. Ecol Evol. 2019;00:1–13. https://doi.org/10.1002/ece3.5215

Ralph SC, Poole GC (2003) Putting monitoring first: Designing accountable ecosystem restoration and management plans. Pages 226-247 In: Montgomery DR, Bolton S, Booth DB, Wall L editors, Restoration of Puget Sound Rivers. University of Washington Press, Seattle, WA

Rippon S (2000) The Transformation of Coastal Wetlands: Exploitation and Management of Marshland Landscapes in North West Europe During the Roman and Medieval Periods. Oxford University Press, Oxford.

Roman CT (2017) Salt marsh sustainability: Challenges during an uncertain future. Estuaries Coasts 40:711–716

Schmidt G, Jenkerson CB, Masek J, Vermote E, Gao F (2013) Landsat ecosystem disturbance adaptive processing system (LEDAPS) algorithm description. United States Geological Survey Open-File Report 2013-1057. https://doi.org/10.3133/ofr20131057

Silliman BR, Grosholz ED, Bertness MD. Editors (2009) Human Impacts On Salt Marshes: A Global Perspective; University of California Press, Berkley

Smith EP (2002) BACI design. pages 141-148 In: El-Shaarawi AH, Piegorsch, WW (eds) Vol. 1, Encyclopedia of Environmetrics. John Wiley & Sons, Ltd, Chichester

Suir GM, Jones WR, Garber AL, Barras JA (2014) Pictorial account and landscape evolution of the crevasses near Fort St. Philip, Louisiana. Mississippi River Geomorphology and Potamology Program, MRG&P Rept. 2. U.S. Army Corps of Engineers, Mississippi Valley Division, Vicksburg, MS

Swarzenski CM, Doyle TW, Fry B, Hargis TG (2008) Biogeochemical response of organic-rich freshwater marshes in the Louisiana delta plain to chronic river water influx. Biogeochemistry 90:49-63

Turner RE, Rabalais NN, Alexander RB, McIsaac G, Howarth RW (2007) Characterization of nutrient and organic carbon and sediment loads and concentrations from the Mississippi River into the northern Gulf of Mexico. Estuaries and Coasts 30:773-790

Turner RE, Kearney MS, Parkinson RW (2018a) Sea level rise tipping point of delta survival. Journal of Coastal Research 34:470-474

Turner RE, McClenachan G (2018b) Reversing wetland death from 35,000 cuts: Opportunities to restore Louisiana's dredged canals. PLOS ONE 13(12):e0207717 https://doi.org/10.1371/journal.pone.0207717.

Turner RE (2011) Beneath the wetland canopy: Loss of soil marsh strength with increasing nutrient load. Estuaries and Coasts 33:1084-1093

Turner RE (2017) The mineral sediment loading of the modern Mississippi River Delta: What is the restoration baseline? Journal of Coastal Conservation 21:867-872

Turner RE, Bodker JE, Schulz C (2018) The belowground intersection of nutrients and buoyancy in a freshwater marsh. Wetlands Ecology and Management 26(2):151-159.

Tweel, A.W. and R.E. Turner (2012) Watershed land use and river engineering drive wetland formation and loss in the Mississippi River birdfoot delta. Limnology and Oceanography 57:18-28

Underwood AJ (1994) On beyond BACI: Sampling designs that might readily detect environmental disturbances. Ecological Applications 4:3-15

USCOE (United States Army Corps of Engineers, New Orleans District) (2004). Davis Pond Freshwater Diversion Project, Mississippi Delta Region, La. Factsheet. USCOE New Orleans District, LA

USCOE (United States Army Corps of Engineers) (1998) Caernarvon Freshwater Diversion Project, Mississippi Delta Region, La. Factsheet. USCOE New Orleans District, LA

Xu H (2006) Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. International Journal of Remote Sensing 27(14):3025–3033

Zedler JB (2017) What's new in adaptive management and restoration of coasts and estuaries? Estuaries and Coasts 40:1–21

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Figure 1. The location and relative position of the two river diversions bringing Mississippi River water into the adjacent wetlands. The area in the immediate flow path of the diverted water (pink) is hydrologically separated on either side by reference sites (blue) (principally levees). The Caernarvon diversion is adjacent to a reference area (location a) that is striped blue; the reference area to the east (location b) is bordered by a road that limits west-to-east flow of the diverted water, although there is some cross-linkage at Reggio, La. The orange vertical line is the path of Hurricane Katrina in 2005.

Figure 2. The percent land in the flow path of the diverted water (open circles), and in the reference (filled circles) site for Data 1 and Data 2. The data were normalized to the land area in 1985. The dotted vertical line indicates when the diversion was first opened. A and B = Davis Pond; C and D = Caernarvon location a; E and F = Caernarvon location b.

Figure 3. The relative differences between the percent land for the 3 comparisons using Data 2.

Figure 4. The percent land in the Coastal Monitoring Program (http://lacoast.gov/crms2/) within the Caernarvon diversion flow path (red dots) and outside (blue dots). The mean and SEM is shown. The data are divided into three periods: 1) small circles representing before the diversion was opened, 2) the medium-sized circles after the diversion was opened, but before hurricane Katrina, and 3) the large circles representing after hurricane Katrina. The results from an ANOVA test of differences between the three periods is indicated by the letters where the upper case blue letters are for the reference site and the lower case red letters are in the diversion flow path. The results from the BACI test is below, indicating a significant change in the percent land after the diversion was opened compared to before the opening for all data (BA1) and after hurricane Katrina (BA4). There was no change detected before the diversion opening and in the first few years afterwards (BA2). The %land after the diversion opened was lower after the hurricane compared to before the hurricane (BA3).

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Table 1. The diversion starting date (year), maximum flow capacity (m^{-3} s^{-1}), study area size (km^2), and anticipated land gain or preservation in agency documents.

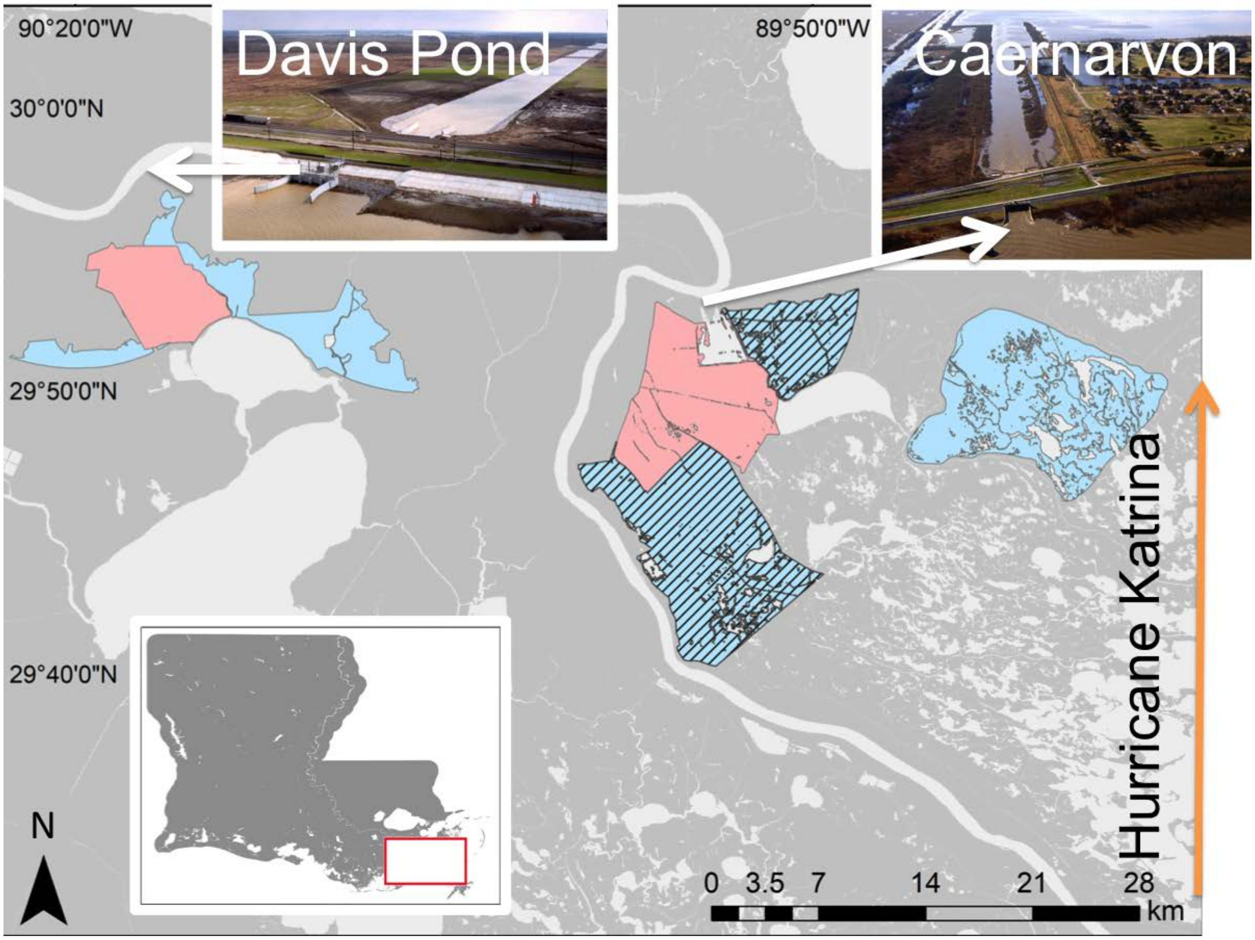
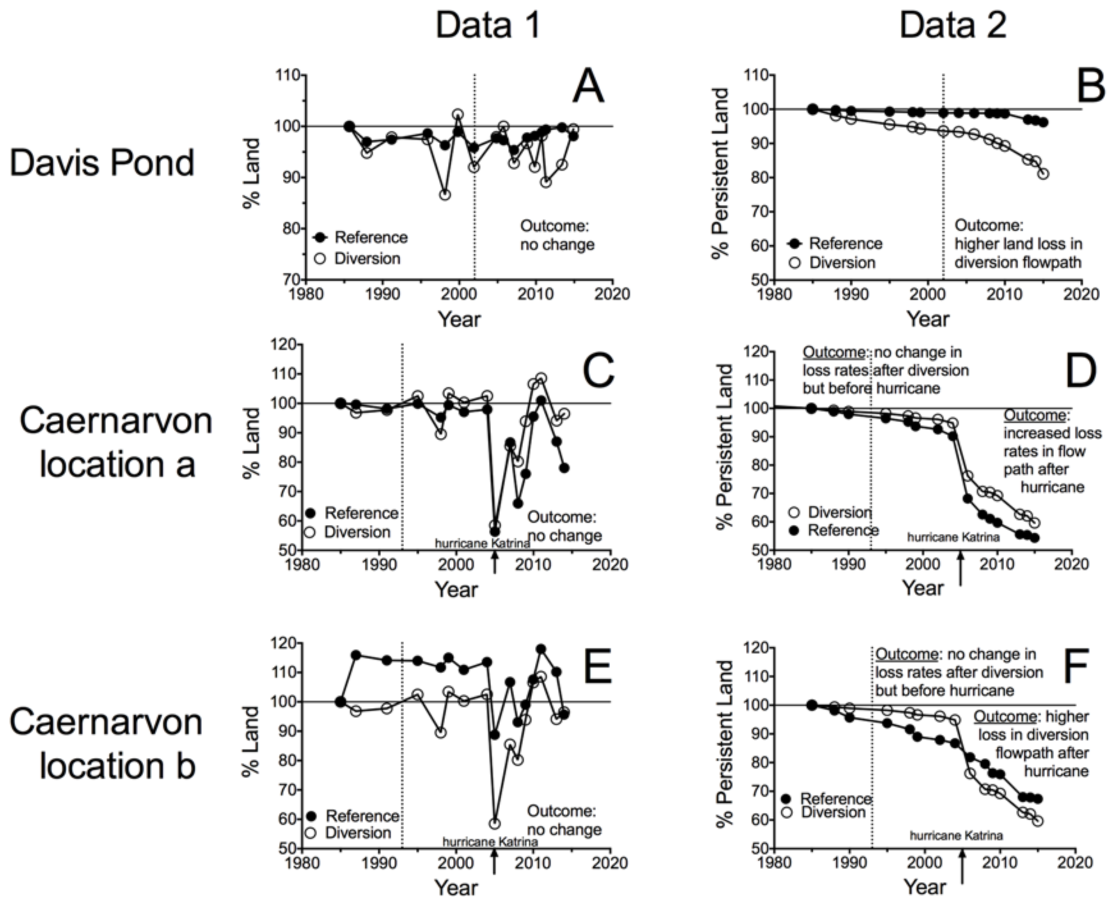


Figure 1. The location and relative position of the two river diversions bringing Mississippi River water into the adjacent wetlands. The Mississippi River is the white channel running from the upper left to the lower right. The Barataria Bay estuary is located on the west bank and the Breton Sound estuary on the east bank of the river. The area in the immediate flow path of the diverted water (pink) is separated on either side by reference sites (blue) (principally levees). The Caernarvon diversion is adjacent to a reference area (location a) that is striped blue; the reference area to the east (location b) is bordered by a road that limits west-to-east flow of the diverted water, although there is some cross-linkage at Reggio, La. The orange vertical line is the path of Hurricane Katrina in 2005.



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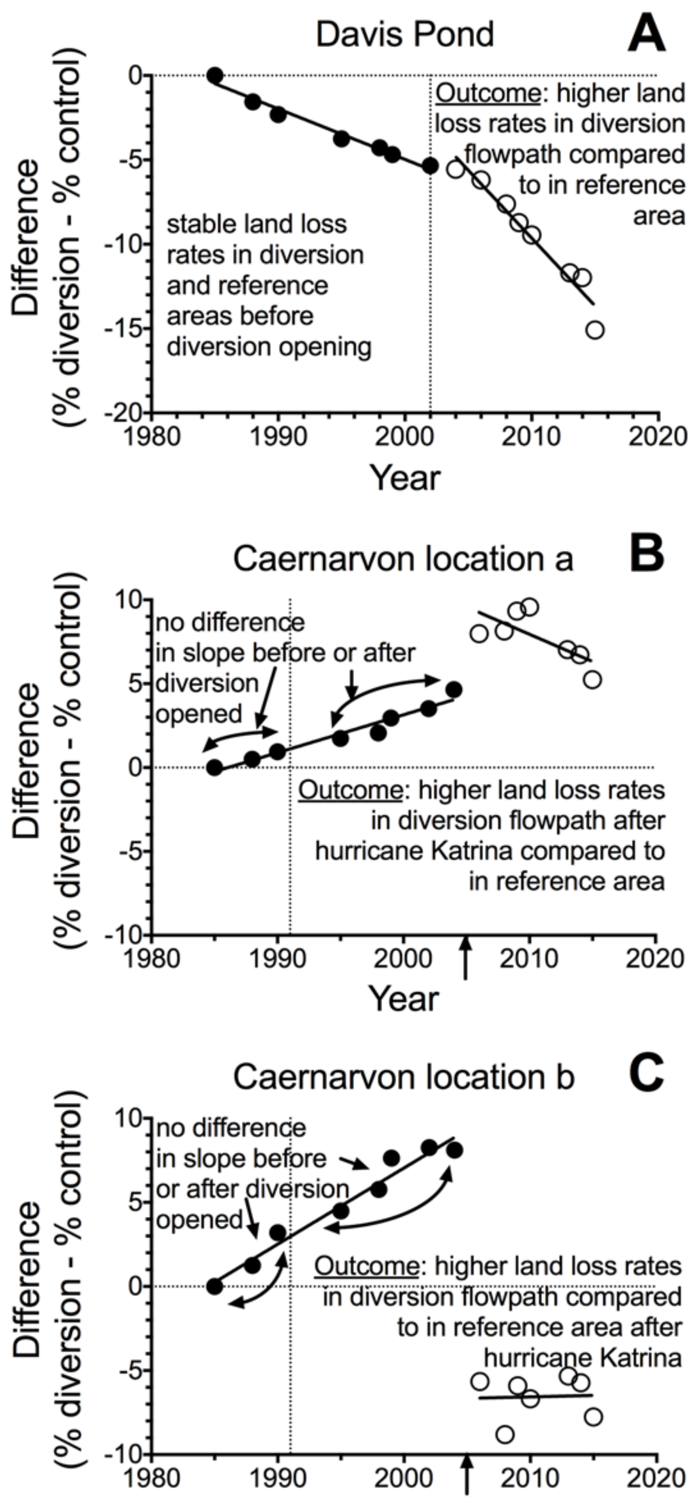
Davis Pond
A
Outcome: higher land loss rates in diversion flowpath compared to in reference area
stable land loss rates in diversion and reference areas before diversion opening
Difference (% diversion - % control)
Year
Caernarvon location a
B
no difference in slope before or after diversion opened
Outcome: higher land loss rates in diversion flowpath after hurricane Katrina compared to in reference area
Difference (% diversion - % control)
Year
Caernarvon location b
C
no difference in slope before or after diversion opened
Outcome: higher land loss rates in diversion flowpath compared to in reference area after hurricane Katrina
Difference (% diversion - % control)
Year

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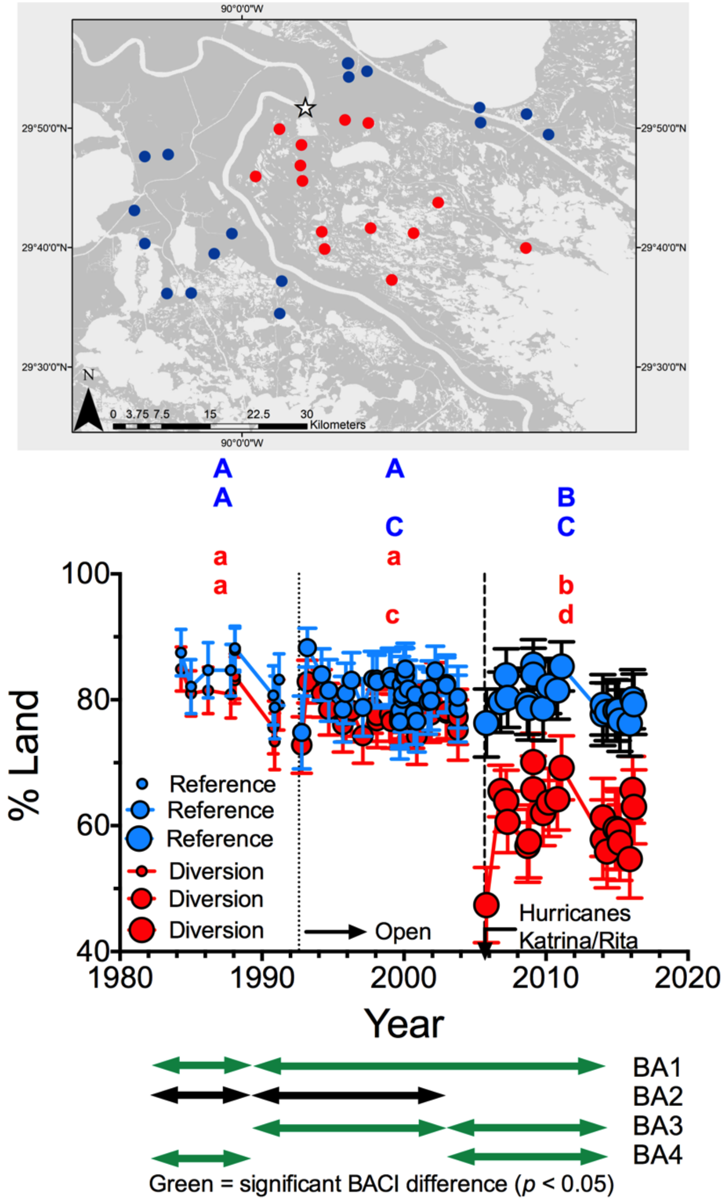

Figure 4. The percent land in the State of Louisiana monitoring sites (Coastal Monitoring Program (http://lacoast.gov/crms2/) within the Caernarvon diversion flow path (red dots) and outside (blue dots). The mean and SEM is shown. The data are divided into three periods: 1) small circles representing before the diversion was opened, 2) the medium-sized circles after the diversion was opened, but before hurricane Katrina, and 3) the large circles representing after hurricane Katrina. The results from an ANOVA test of difference between the three periods is indicated by the letters where the upper case blue letters are for the reference site and the lower case red letters are in the diversion flow path. The results from the BACI test is below, indicating a significant change in the percent land after the

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Table 1. The diversion starting date (year), maximum flow capacity (m^{-3} s^{-1}), study area size (km^2), and anticipated land benefited or preserved described in agency documents (20 years).

Area	Year first Opened	Capacity (m^{-3} s^{-1})	Average flow (m^{-3} s^{-1})	---Study Area--- Land (km^2)	Water (km^2)	Size Project area (km^2)	Projected area benefited (km^2)	Projected area preserved (km^2)	Source
Davis Pond									
Diversion	2002	306	46.1	39	1.0	3,278	3,144	134	(USCOE 2004)
Reference				56	0.4	(sum benefited and preserved)			
Caernarvon									
Diversion	1991	227	41.8	62	10.4	396	332	65	(USCOE 1998)
Reference				77	26				